

Unclas
00/18 12097

Bellcomm

955 L'Enfant Plaza North, S.W.
Washington, D. C. 20024

date: August 6, 1971

to: Distribution

B71 08016

from: S. S. Fineblum, A. S. Haron

subject: Review of Results of Cryogenic O₂ Tank
Redesign Program - Case 320

MEMORANDUM FOR FILE

Activities conducted by numerous organizations over a one-year period following the failure of the Apollo 13 oxygen storage system included the redesign of the cryogenic oxygen storage system, modification of the hardware, theoretical and experimental prediction of performance, and post-flight evaluation. The principal results of such efforts were recently summarized at an MSC Symposium⁽¹⁾ and an APO Wednesday Morning Meeting.⁽²⁾

I. Hardware Development

The basic changes were the elimination of destratification fans and motors, the splitting of the heater into three elements to provide full, two-thirds, or one-third power and the installation of an additional oxygen tank on Apollo 14. A temperature sensor was added to provide for direct monitoring of heater temperature. There were also some plumbing and signaling changes.

Noteworthy efforts by Beech Aircraft were the construction of the new sheathed wiring, new techniques of brazing and the various accelerated qualification tests.

II. Stratification Analysis

Among the efforts to explain and predict stratification, Bellcomm generated a two-fluid stratification model (useful in analyzing pressure collapse at high oxygen quantities) and a conductive-radiative model (useful in analyzing heater temperature limits at low oxygen quantities). Based on Apollo 14 pressure data, the stratification model predicts that only 1% of the total fluid interacts with the heater during the repressurization period. Following heater deactivation the thermal energy gradually spreads by conduction and convection to the remaining bulk fluid.



The conductive-radiative model predicts heater temperatures in the total absence of convection, a limiting case. The latter predictions are in reasonable agreement with flight data for the very low gravity attitude-hold conditions.

The National Bureau of Standards provided services to various investigators through assembling and disseminating thermophysical property data in the form of charts, tables and/or computer tapes.

The Boeing Co. performed analyses using C. K. Forester's two-dimensional model dealing with the simultaneous solution of the time-dependent conservation of mass, energy and momentum equations. Predictions of temperature and pressure variation with time under various "g" loads agreed fairly well with flight data from Apollos 12 and 14. But, it was found that the choice of effective heater surface area had a significant effect on the accuracy of the correlation. Use was also made of the empirical Rayleigh heat transfer equation in predicting heater temperature within 22% accuracy.

The TRW Systems Group numerically solved the compressible Navier-Stokes equations in two dimensions. This approach was found to consume excessive computer time. It predicted the magnitude of pressure decay fairly accurately, but the decay rate prediction was 70% slower than shown by flight data. The effect of taking tank stretch with pressure increase into consideration produced 40% difference in the pressure rise rate.

The NASA (Ames) team determined the usefulness of increasing the rate and/or reversing the direction of spacecraft rotation as means of alleviating stratification. This technique was found to be capable of reducing the pressure build-up due to stratification by 50%. No attempt was made to compare the results of this analysis with flight data.

The NASA (Langley) team generated a one-dimensional model with cylindrical geometry, under perfect zero-g conditions. This investigation resulted in plots of heater temperature and pressure versus time for oxygen quantities ranging between 95% and 12% in addition to plots of temperature and density profiles within the tank. These predictions were in good agreement with Apollo 14 flight data under attitude-hold conditions. However, for PTC rotation modes, the model over-predicted both the heater temperature and the heater cycle time.



North American Rockwell developed a semi-empirical design-oriented model which split the fluid into three cells, two interacting with the heater internally and externally, and the third encompassing the remaining bulk fluid. Modes of heat transfer considered were a combination of laminar free convection at low-g, radiation, and conduction. A unique approach was to incorporate fluid properties at a reference temperature which was empirically determined as a function of density on the basis of flight data of Apollo 14. The whole procedure is aimed at predicting the tank pressure and heater temperature as a function of flight time, heater duty-cycle and acceleration level. Comparison of this model's predictions with flight data of Apollo 14 indicates reasonable agreement.

III. Systems Models

TRW Systems Group predicted the responses of the Apollo Cryogenic System with two separate, coupled models:

A model of the connecting lines and fittings was established to predict the actual flow rate from each tank to the separate branches of the supply system. The temperature and pressure of the tanks and the demands of the separate systems were the required inputs.

A model of the tanks which requires as inputs the flow rate of each tank and thermal conditions predicts tank pressure. The program also incorporates stratification predictions. The National Bureau of Standards was the source of the equation of state and data for the other thermophysical properties. The effects of heater, isolation valve, or other failures can be simulated, as well as effects of stratification. The program requires inertial conditions that have not been completely computed. However, such computations are in work and we are told to expect final results soon. This model, constructed for both the CSM oxygen and hydrogen tanks, is the most comprehensive.

The Mission Planning and Analysis Division of MSC developed with Lockheed Electronics of Houston a pre-mission planning and analysis method, which was later extended and enlarged so that it can do both real time and post-flight analysis. This program can compute the oxygen flow sharing between the ECS and EPS systems from the separate tanks. Vent thrust is computed as a function of the pressure change and the mass flow demand of the supply system. The temperature, pressure, and density are computed by use of National Bureau



of Standards data. The heat leak is computed with a simple thermal model. As outputs, the pressure and temperature profiles are predicted. The program could be adapted to similar problems of the space shuttle.

It is obvious that the above two effects are quite similar in form content and results. This conscious duplication was used by NASA to support the analysis, redesign and mission planning for the cryogenic oxygen system. This duplication was useful because confidence was established in the predicted performance of Apollo 14. The necessity to accomplish design and development work in a short period of time without sufficient experimental maturity was clearly sensed. The confidence generated by redundant programs was thus very important in the planning and success of the mission.

IV. Test Programs

Lands and Ried of MSC performed a study on the simulation of thermal mixing by the injection of dye in a full scale plexiglass model of the oxygen tank and photographing its diffusion rates and patterns. Care was taken to use a dye with the same specific gravity as the test fluid to avoid any 1-G distortions and to have the dye injected at such a small velocity as to minimize the inertial effects.

The analogy of dye diffusion to conduction requires a measurement of the concentration gradients as a function of time. This measurement was not attempted. However, there was some attempt to study the persistence of fluid motion by observing the relative movement of the dye. There are no flight observations that clearly support the results of those experiments. Their use of Reynolds number to scale the tank velocity may be an oversimplification.

The Materials Technology Branch of MSC supported the analysis of the Apollo 13 fire and the redesign for the Apollo 14, with a comprehensive testing program. Procedures were developed in connection with the accident investigations and for testing the new heater wires. Various methods of partially damaging the wires and trying to simulate high voltage transients in order to get ignition and spark were used.



In addition, there was a test of the external oxygen circulation loop that was one possible design alternative to the oxygen tank fans. The feasibility of an external circulation loop was demonstrated successfully.

A 1-G "blowdown" of the system starting from full pressure and 20% remaining, down to 150 psi and ~3% remaining, was performed with no operational difficulties.

V. Flight Performance

Robert Rice of MSC Propulsion and Power Division coordinated the Task Team effort. He recently pointed out that the unique conditions of the redesign of the Apollo 14 CSM oxygen system required an unprecedented dependence upon analysis. The redesign, initiated as the response to the Apollo 13 incident, had to be accomplished and verified, and the hardware installed and operated within a very short period of time. All the people contributing to the analysis met periodically to present their results and to speed the integration of their effort to hardware and operational decisions. The three results of team effort were: the evolution of a system in time for installation and flight, the establishment of confidence in the operational virtues of such a system and finally the training of the flight support team for real time mission backup.

The problem of high heater temperature, which was anticipated because of the removal of the tank fans, was complicated by movement of the heater sensor to a hotter spot than originally planned.

There was also some early apprehension that the uncirculated oxygen would experience stratification and then sudden destratification. The Apollo 14 flight showed that this occurrence does not interfere with the functioning of the tank.

From a technical point of view, the post flight analysis showed that the Apollo 14 system was relatively insensitive to a single check valve failure, that the observed heater temperature was a very sensitive function of the sensor location on the heater and that the system was capable of supporting high flow rates. It was also shown that the quantities based on temperature, pressure and equation of state were not significantly different from those indicated by the capacity probe.



- 6 -

The analysis team, which included Bellcomm, reported directly to the ASPO manager.

Reference (1), containing the full text of all papers presented at the recent Symposium, is available by contacting the writers.

Sol Fineblum
S. S. Fineblum

A. S. Haron
A. S. Haron

2031-SSF-jf
ASH

Attachment
References



REFERENCES

1. "MSC Cryogenics Symposium Papers", NASA Manned Spacecraft Center, Document #MSC-04312, May 20-21, 1971.
2. J. A. Saxton, "Apollo Oxygen Tank Performance Presentation", Memorandum for File, B71 06015, June 14, 1971, Case 320.



Subject: Review of Results of Cryogenic O₂ Tank
Redesign Program - Case 320

From: S. S. Fineblum, A. S. Haron

Distribution List

NASA Headquarters

A. S. Lyman/MAP
W. E. Stoney/MAE

Bellcomm

G. M. Anderson
A. P. Boysen, Jr.
J. P. Downs*
D. R. Hagner
J. J. Hibbert
W. W. Hough
D. P. Ling*
J. Z. Menard
P. F. Sennewald
J. W. Timko*
R. L. Wagner
J. E. Waldo
M. P. Wilson*
All Members of Department 2031
Central Files
Department 1024 File
Library

*Abstract Only